Field Crops Research 118 (2010) 152–157

Contents lists available at ScienceDirect

Field Crops Research

journal homepage: www.elsevier.com/locate/fcr

Changes in juice quality and sugarcane yield with recurrent selection for sucrose

Sarah E. Lingle[a,*], Richard M. Johnson[b], Thomas L. Tew[b], Ryan P. Viator[b]

[a] USDA-ARS, 1100 Robert E. Lee Boulevard., New Orleans, LA 70124, USA
[b] USDA-ARS, 5883 USDA Road, Houma, LA 70360, USA

ARTICLE INFO

Article history:
Received 30 March 2009
Received in revised form 11 May 2010
Accepted 13 May 2010

Keywords:
Breeding
Juice Quality
Recurrent selection
Saccharum
Sucrose
Sugarcane
Yield

ABSTRACT

Sugarcane (*Saccharum* spp. hybrids) breeding programs in Louisiana have made improving sucrose content a top priority because a short growing season limits cane yield. Using a recurrent selection strategy, the cultivars with the highest sucrose content are crossed, and a new generation of cultivars is selected from the progeny. This study was designed to determine how selection primarily for sucrose content has modified physiological characters, and impacted sucrose content and yield. Five cultivars were randomly selected from each of seven generations of recurrent selection in Louisiana and planted in two experiments. The plant and first stubble crops were harvested late in the harvest season from each experiment. Cane yield and juice quality were determined. Cultivars from the last three generations were superior to cultivars from the first three generations for Brix % cane, sucrose % cane, purity, theoretically recoverable sugar (TRS), cane yield and sugar yield. Fiber % cane was not different among the generations. Selection primarily for sucrose has increased Brix % cane from 14% to 16%, sucrose % cane from 12% to 14%, purity from 82.5% to 87.3%, and TRS from 98 to 122 kg Mg^{-1}. A plateau in juice quality and sucrose yield in the last three generations may indicate that: (1) Louisiana's short growing season may restrict sucrose accumulation; (2) the genetic potential for late season juice quality has been reached with currently available germplasm; or (3) the inclusion of lower juice quality *Saccharum spontaneum* germplasm into the breeding program in order to increase disease tolerance, cold tolerance, and ratooning ability has diluted the effect of recurrent selection for sucrose.

Published by Elsevier B.V.

1. Introduction

Sugarcane is an ancient crop with a complex genetic history. Until the 20th century, sugarcane industries throughout the world relied on "noble canes" (*Saccharum officinarum* L.) for sugar production. However, since early in the 20th century most of the production world-wide has been derived from polyploid, aneuploid interspecific hybrids of two or more basic *Saccharum* species (Hogarth, 1987). The first interspecific cultivar brought to Louisiana, POJ 234, was bred and selected in Java and released in Louisiana in 1922 (Gravois and Bischoff, 2008). This and other hybrid cultivars originally developed in India and Indonesia formed the basis for subsequent breeding efforts in Louisiana.

Sucrose yield in sugarcane is a product of cane yield and sucrose content of the cane. While both cane yield and sucrose content are important, increasing sucrose content has been a priority in the Louisiana sugarcane breeding programs, because cane yield is constrained by a short growing season. The length of the growing season depends on the date of the last killing frost in the spring, and the date of harvest in the fall. In Louisiana, this can be as little as seven months. Breaux (1984) described the modified recurrent selection for sucrose content system used in Louisiana thus: "(a) select the highest sucrose phenotypes available; (b) intercross these varieties; (c) grow large seedling populations (60–80,000 annually); (d) select rigidly for sucrose; and (e) intercross the selections to produce still another improvement cycle." Breaux demonstrated that by 1984, four cycles of recurrent selection for sucrose content had increased mean normal juice sucrose (juice sucrose as it exists in the stalk; Legendre and Henderson, 1972) of selections from 9.7% in the first cycle to 14.0% in the fourth cycle. This process has since been largely continued for two more cycles, although a basic breeding program which began in 1965 to introgress new *S. spontaneum* germplasm into Louisiana-adapted cultivars (Dunckelman and Breaux, 1972) contributed to the last two cycles.

This experiment was conducted to measure changes in growth and sugar accumulation parameters that resulted from selection for primarily for sucrose content (Lingle et al., 2009). It also afforded an opportunity to directly compare cane yield and sucrose content of cultivars from each generation and test the hypothesis that recurrent selection for sucrose content has increased sucrose content and sucrose yield in sugarcane.

* Corresponding author. Tel.: +1 504 286 4488; fax: +1 504 286 4419.
E-mail address: Sarah.Lingle@ars.usda.gov (S.E. Lingle).

0378-4290/$ – see front matter. Published by Elsevier B.V.
doi:10.1016/j.fcr.2010.05.002

Table 1
Thirty-five sugarcane cultivars representing seven generations from six cycles of recurrent selection for primarily for sucrose content in Louisiana, year of release and parentage.

Generation	Cycle	Cultivar	Year of release	Parents	
				Female	Male
1	0	Co 281	1930	POJ 213	Co 206
1	0	Co 290	1933	Co 221	D 74
1	0	CP 807	1930	US 1643	Unknown
1	0	POJ 234	1922	Black Cheribon[a]	Chunnee[b]
1	0	POJ 2878	1928	POJ 2364	EK 28
2	1	CP 29-103	1939	POJ 2725	CP 1165
2	1	CP 29-116	1936	POJ 2725	CP 1165
2	1	CP 34-120	1942	Co 281	POJ 2878
2	1	CP 36-105	1945	Co 281	CP 1165
2	1	CP 44-101	1949	Co 281	CP 1165
3	2	CP 44-155	1949	CP 33-229	CP 33-224
3	2	CP 48-103	1955	CP 29-320	CP 290
3	2	CP 52-68	1958	CP 29-320	CP 38-34
3	2	CP 53-18	NR[c]	F 36-819	CP 48-126
3	2	CP 55-30	1963	CL 41-142	CP 48-126
4	3	CP 61-37	1967	CP 48-103	CP 55-38
4	3	CP 62-258	NR	CP 53-18	CP 33-224
4	3	CP 65-357	1973	CP 52-68	CP 53-17
4	3	L 60-25	1966	CP 52-68	CP 48-103
4	3	L 65-69	1972	CP 52-1	CP 48-103
5	4	CP 70-321	1978	CP 61-39	CP 57-614
5	4	CP 72-370	1980	CP 61-37	CP 52-68
5	4	CP 73-351	1981	CP 65-357	L 65-69
5	4	CP 76-331	1984	CP 65-357	L 65-69
5	4	CP 79-318	1987	CP 65-357	L 65-69
6	5	CP 89-831	NR	CP 72-370	CP 76-331
6	5	HoCP 85-845	1993	CP 72-370	CP 77-403
6	5	LCP 81-030	NR	CP 61-37	CP 73-351
6	5	LCP 85-384	1993	CP 77-310	CP 77-407
6	5	LCP 86-454	1994	CP 77-310	CP 69-380
7	6	HoCP 00-950	2007	HoCP 93-750	HoCP 92-676
7	6	HoCP 01-534	NR	HoCP 92-654	LCP 85-384
7	6	HoCP 96-540	2003	LCP 85-454	LCP 85-384
7	6	L 97-128	2004	L 81-10	LCP 85-384
7	6	L 99-226	2006	CP 89-846	LCP 81-030

Generation 1 cultivars were foundation cultivars developed in other areas and used to initiate the modern breeding effort in Louisiana.
[a] *Saccharum officinarum*.
[b] *S. barberi*.
[c] NR, not released.

2. Materials and methods

2.1. Cultivar selection

The released or near-released cultivars that were used as parents of subsequent generations have been maintained at the USDA-ARS Sugarcane Research Laboratory's Ardoyne research farm near Schriever, LA. Cultivars were assigned to a recurrent selection generation based on the generation of their parents. Five cultivars were selected at random from each of seven generations of selection primarily for sucrose content. The cultivars, their parentage, and year of release are listed in Table 1.

2.2. Crop management

In October 2004, four whole stalks of 35 cultivars (Table 1) were planted in single-row plots, 4.9 m long and 1.8 m apart. The plots were located at the Ardoyne Research Farm (N 29 38′ 15″ W 90 50′ 21″). This planting was designated as Experiment 1. There were four replications of the cultivars arranged in a randomized complete block design. The entire experiment was surrounded by a buffer row of a commercial cultivar. The soil was Cancienne silt loam and Cancienne silty clay loam (fine-silty, mixed, superactive, nonacid, hyperthermic Fluvaquentic Epiaquepts). Seed cane of cultivars from Generation 1 through 6 was obtained from the historic nursery at Ardoyne Research Farm. Seed cane of Generation 7 cultivars came from infield tests on the same farm. Plots were fertilized by side-dressing with 112 kg ha^{-1} N, 15 kg ha^{-1} P, and 55 kg ha^{-1} K in the spring of each year (2005 and 2006). Plots were not irrigated. Plots were harvested as described below on 7 December 2005 (plant cane) and 12 December 2006 (first stubble cane).

Experiment 2 was planted in November 2006 in a different area of the same research farm in Cancienne silt loam. Seed cane for all the plots came from the first replication of Experiment 1. This experiment also consisted of four replications of the 35 cultivars arranged in a randomized complete block. Plot sizes were identical to those in Experiment 1. These plots were fertilized as above in the spring of 2007 (plant cane) and 2008 (stubble cane). Experiment 2 was harvested on 27 November 2007 (plant cane) and 15 December 2008 (stubble cane).

2.3. Harvesting and quality analyses

Plots were harvested using a chopper harvester and a weigh wagon as described by Johnson and Richard (2005). The weight of each harvested plot was used to calculate cane yield (Mg cane ha^{-1}). A random sample of billets (about 10 kg) was collected from each plot during harvest. The billets were chipped and shredded using a pre-breaker (CAMECO Industries, Inc., Thibodaux, LA), and juice was expressed from a 1 kg subsample of the chipped stalks by pressing at 21 MPa for 2 min. The remaining fiber cake was weighed, dried at 66 °C for 72 h in a forced-air oven, and reweighed to determine the fiber content.

Expressed juice was analyzed for Brix (% of soluble solids) by refractometer and for Pol (apparent sucrose) by saccharimeter. Apparent purity was calculated as Pol/Brix × 100. Juice Brix, and Pol were used to calculate brix % cane and sucrose % cane. Brix % cane (B), sucrose % cane (P) and fiber % cane (F) were then used to calculate theoretically recoverable sucrose (TRS) using the formula TRS (in pounds ton^{-1} cane) = $(0.28 \times P - 0.08 \times B) \times (100 - (56.67 \times F/100))$. The value was then converted to kg Mg^{-1} cane. This formula takes into account the reduction in sucrose extractability due to fiber and the reduction of potential sucrose crystallization during processing due to impurities in the juice (Legendre, 1992). Sugar yield (kg sugar ha^{-1}) was calculated as TRS × cane yield (Legendre, 1992).

2.4. Statistical analyses

Data were analyzed using the Mixed Procedure (PROC MIXED) of SAS 9.2 for Windows (Littell et al., 1996). The experiment was analyzed as a split plot with experiment as the main plot, the two harvests within each experiment as the subplots, and the seven generations as sub-subplots. The two experiments, seven generations, and two harvests per experiment were treated as fixed effects. No attempts were made to compare cultivars within generations; cultivar was treated as a random effect. The differences between least square means were calculated using the PDIFF option of PROC MIXED (Littell et al., 1996) at a significance level of $P \leq 0.05$.

3. Results

3.1. Growth environments

Average weekly temperatures and weekly cumulative rainfall for each year are shown in Fig. 1. The plant-cane crop of the first experiment and the stubble crop of the second experiment were both affected by hurricanes at the end of August and mid-September 2005 and 2008, respectively. This caused crop lodging, which can reduce yield (Singh et al., 2002) and makes harvesting difficult. There was 1267 mm rain in the growing season of 2005, 1160 mm rain in 2006, 1437 mm rain in 2007, and 1432 mm rain in 2008. There were mild, pre-harvest freezes on 6 December 2005 (0 °C), 21–22 November (0 °C both nights) and 4–5 December 2006 (−1 °C and −3 °C), and 19 November (0 °C), 22 November (0 °C), and 2 December 2008 (−1 °C). These freezes killed the terminal bud on the stalk, but were not sufficient to damage the stalks. In all four years the plots were harvested late in the harvest season, which in Louisiana begins about 1 October and usually ends in mid- to late December.

3.2. Analysis of variance

Experiment had a significant effect on juice purity, cane yield, and sugar yield (Table 2). Generation had a significant effect on all parameters measured except fiber % cane, while crop had a significant effect on Brix % cane, sucrose % cane, fiber % cane, cane yield and sugar yield. There was a significant interaction between experiment and crop for all parameters except fiber. This was because in the two experiments, the differences between crops were opposite each other (Table 3). That is, in the first experiment, Brix % cane, sucrose % cane, and purity were lower in the stubble than the plant crop, while in the second experiment they were higher in the stubble crop. In Experiment 1, cane yield and sugar yield were much higher in the stubble crop than in the plant crop, but in Experiment 2, yields of the two crops were comparable. The differences between crops and experiments were most likely due to

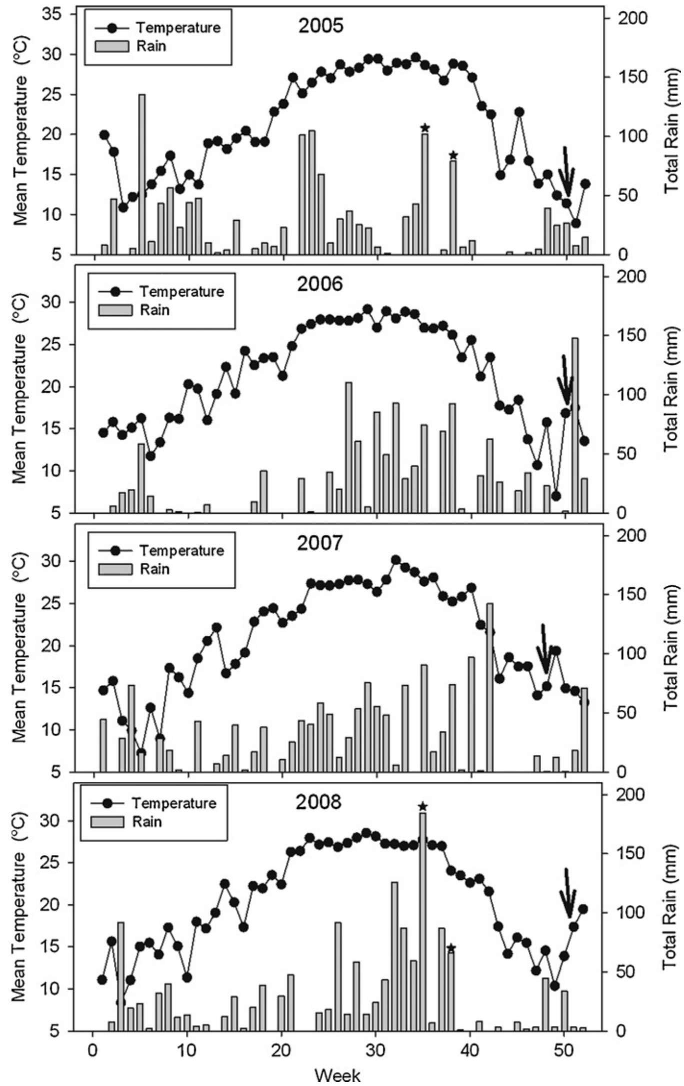

Fig. 1. Weekly mean temperature and rainfall at Ardoyne Farm in Schriever, LA in 2005–2008. Tropical storms in 2005 and 2008 are indicated with stars. Harvest dates are indicated with arrows.

environmental differences between years, although poor seed cane and the late planting date may have had an effect on plant-cane establishment in Experiment 1. The significant effect of generation (Table 2) was the same in both crops from both experiments. The experiment × generation interaction was not significant for any parameter, and the generation × crop interaction was significant only for cane yield and sugar yield.

3.3. Differences among generations

The last three generations were superior to the first three generations for all parameters except fiber (Table 4). Generation 4 was intermediate. The newest cultivars, in Generation 7, had the highest mean Brix % cane, sucrose % cane, and juice purity, and therefore the greatest TRS of the seven generations, although these were statistically the same as those from Generations 5 and 6. Generation 7 cultivars had lower cane yields than Generation 5 and 6 cultivars, although the difference was not significant. Sugar yield was slightly higher in cultivars from Generations 5 and 6 than in Generation 7 because of the higher cane yield in Generations 5 and 6, but again the difference was not significant. In 2005–2007, up to nine stalks were removed from the Generation 1 and Generation 7 plots

Table 2
Statistical significance (P values) of fixed effects for brix % cane, sucrose % cane, juice purity, fiber, theoretically recoverable sugar (TRS), cane yield and sugar yield measured on five cultivars in each of seven recurrent selection generations.

Source	df	Brix % cane	Sucrose % cane	Purity	Fiber % cane	TRS	Cane yield	Sugar yield
$P > F$								
Experiment (E)	1	0.0783	0.5312	0.0103	0.1494	0.6798	0.0001	0.0010
Generation (G)	6	0.0016	0.0009	0.0007	0.3938	0.0010	0.0072	0.0001
Crop (C)	1	0.0479	0.0496	0.2168	0.0022	0.2308	0.0001	0.0001
E × C	1	0.0001	0.0001	0.0001	0.0827	0.0001	0.0001	0.0001
E × G	6	0.8817	0.9170	0.7448	0.3891	0.9542	0.1646	0.2415
C × G	6	0.4307	0.5176	0.7346	0.2090	0.5567	0.0342	0.0013
E × C × G	6	0.7988	0.5922	0.0320	0.0470	0.6261	0.2007	0.1580

There were two experiments, and plant-cane and stubble crops were harvested from each experiment. Effects were considered significant at $P < 0.05$.

Table 3
Least square means of brix % cane, sucrose % cane, fiber, purity, theoretically recoverable sucrose (TRS), cane yield and sugar yield from two experiments and two crops per experiment across seven generations of recurrent selection for sucrose in sugarcane.

	Crop	Brix % cane	Sucrose % cane	Fiber	Purity %	TRS kg Mg^{-1}	Cane yield Mg ha^{-1}	Sugar yield Mg ha–
Experiment 1	Plant	15.5a[1]	13.2a	12.7b	85.3b	113.3a	76.6b	8.7b
	Stubble	14.8b	12.4b	13.2b	83.7c	105.1b	122.7a	13.1a
Experiment 2	Plant	14.4c	12.1c	12.6b	84.1c	103.2b	87.6b	9.1b
	Stubble	15.5a	13.4a	14.0a	86.3a	114.0a	79.7b	9.2b

[1] Letters within a column followed by the same letter are not significantly different by the LSD test at $P \leq 0.05$.

Table 4
Least square means of brix % cane, sucrose % cane, fiber, purity, theoretically recoverable sucrose (TRS), cane yield and sugar yield across two experiments and two crops per experiment for sugarcane cultivars from seven generations of recurrent selection for sucrose.

Generation	Brix % cane	Sucrose % cane	Fiber	Purity %	TRS kg Mg^{-1}	Cane yield Mg ha^{-1}	Sugar yield Mg ha^{-1}
1	14.1c	11.7c	13.3	82.5c	98.3c	78.4cd	7.9cd
2	14.2c	11.7c	14.0	82.4c	97.2c	66.7d	6.2d
3	14.8bc	12.4bc	12.7	83.5bc	104.9bc	73.7cd	7.6cd
4	15.3ab	13.1ab	13.2	85.3ab	111.5ab	88.0bcd	9.6bc
5	15.6ab	13.6a	13.3	87.1a	117.3a	110.3ab	12.8a
6	15.2ab	13.2ab	13.2	86.4a	113.0ab	118.5a	13.3a
7	16.0a	14.0a	12.4	87.3a	121.7a	102.3abc	12.4ab

Yields of Generation1 and Generation 7 cultivars for both crops of the first experiment and the plant cane crop of the second experiment were underestimated by about 13% due to preharvest removal of stalks for another part of the study.
Letters within a column followed by the same letter are not significantly different by the LSD test at $P \leq 0.05$.

for another part of the experiment (Lingle et al., 2009). This would have decreased cane yield in these plots by about 13%, which may have been enough to alter the analysis of variance for cane yield. However, the analysis of variance for 2008, in which no stalks were removed from any plot before harvest, gave the same results as the earlier years.

4. Discussion

4.1. Components of sucrose yield

Breaux (1984) used data from the third stage of selection from the Louisiana breeding program to demonstrate that four cycles of recurrent selection for sucrose had increased sucrose content in sugarcane in Louisiana. In our study we directly compared five cultivars from each of seven generations resulting from six cycles of recurrent selection for sucrose. Six cycles of recurrent selection primarily for sucrose have increased Brix from 14.1% to 16.0% cane, and increased sucrose % cane from 11.7% to 14.0% cane (Table 4). These changes improved TRS by more than 20 kg Mg^{-1} cane. These improvements, and the increase in cane yield, resulted in an improvement in sugar yield of about 4 Mg ha^{-1}. It can be concluded that recurrent selection for sucrose has been successful in increasing sucrose yield in sugarcane in Louisiana.

There were no significant differences in Brix % cane, sucrose % cane, purity and TRS in the last three generations (Table 4). This may be a temporary plateau not uncommon in breeding programs (Edmé, 2009, personal communication.) The Generation 7 cultivars had the highest mean Brix % cane, sucrose % cane, purity, and TRS, suggesting that the generation to come may have significantly greater quality. However, this lack of progress may also indicate that the potential for high sucrose late in the harvest season has been reached in the current germplasm. While the average sucrose % cane was greater in Generation 7 than Generation 1, the maximum sucrose % cane observed in any plot, about 16%, did not increase with generation (Fig. 2). This may represent a physiological limit for sucrose accumulation for sugarcane grown in Louisiana. The data from our experiment suggests that Generation 7 cultivars

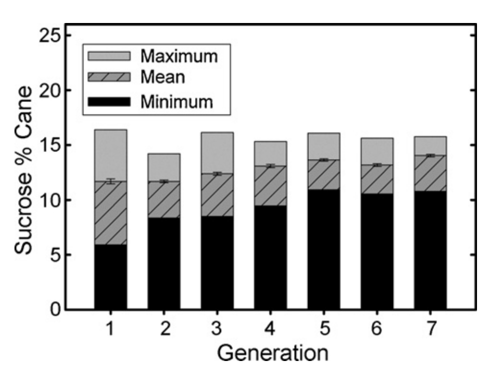

Fig. 2. Minimum, maximum and mean sucrose % cane of sugarcane from seven generations of recurrent selection for sucrose across two experiments, with two crops (plant and stubble) per experiment. Each generation was represented by five cultivars. Vertical bars on mean represent ±SE ($n = 80$).

reduced the gap between sucrose content achieved and the maximum achievable. Further selection may bring new cultivars closer to that 16% limit, but getting beyond it may require a different strategy.

Is the apparent limit to sucrose accumulation in Louisiana sugarcane due to Louisiana's climate, restricted genetic variability in the germplasm, or the selection strategy used in the program? The effective growing season in Louisiana is about 230 days from early spring growth until growth mostly ceases. Muchow et al. (1996) demonstrated that sucrose concentration on a dry weight basis reached a maximum about 300 days after planting or ratooning in Australia's high input, tropical conditions. Inman-Bamber et al. (2002) concluded that whole stalk sucrose content is mostly related to the relative proportion of young internodes with low sucrose content and older internodes with high sucrose content. In a short growing season, the ratio of young to old internodes will be greater, the sucrose content of whole stalks will be less, and the purity of the juice will be lower than in a longer growing season. Lingle et al. (2009) demonstrated that in Louisiana an internode developing during the peak growth period took about 600 °C d (base temperature 18 °C), about 60 days, to reach maximum sucrose content. In the short growing season, internodes developing late in the growing season would not have time to reach maximum sucrose content before harvest. The maximum sucrose content reported by Lingle et al. (2009) for an internode from Generation 7 was about 0.4 g g DW^{-1}. Muchow et al. (1996) reported that the sucrose content of whole stalks of sugarcane grown across a range of environments was about 0.48 g g DW^{-1}, while Berding (1997) indicated a range of sugar content of 0.44–0.6 g g DW^{-1} in unselected sugarcane clones. Clearly there is room for improvement of sucrose content in Louisiana sugarcane.

Deren (1995) demonstrated that all of the commercial sugarcane cultivars grown in Louisiana and Florida have cytoplasm from only three *S. officinarum* genotypes, and the pedigrees of all commercial cultivars in these states can be traced to seventeen foundation genotypes, mostly *S. officinarum*. *S. officinarum* is the source of most of the high sucrose genes in sugarcane (Ming et al., 2001, 2002a,b), so including new *S. officinarum* germplasm in the breeding program might be beneficial. However, Jannoo et al. (1999) and Aitken et al. (2006) demonstrated that most of the molecular marker diversity present in *S. officinarum* is present in the interspecific germplasm used in breeding programs. It seems unlikely that much more diversity within *S. officinarum* is left to be exploited.

In 1965, the Louisiana breeding program expanded what it called a basic breeding program (Dunckelman and Breaux, 1972) to introduce higher cane yield, erectness and suitability for mechanical harvesting, resistance to diseases (especially to sugarcane mosaic), greater cold tolerance, and greater resistance to the sugarcane borer by crossing diverse *S. spontaneum* genotypes with existing commercial cultivars, then backcrossing several times to commercial types to restore stalk weight and juice quality. This new germplasm was included in new cultivars from Generations 6 and 7. The introgression of new *S. spontaneum* genes into the breeding program may have limited the increase in sucrose content achieved by selection since *S. spontaneum* genotypes do not store sucrose, although studies with molecular markers have demonstrated QTLs from *S. spontaneum* that are associated positively as well as negatively with sugar-related traits (Ming et al., 2001; Reffay et al., 2005; Alwala et al., 2009).

In developing new commercial cultivars, selection for increased cane yield concurrently with sucrose content may also have offset some gains in sucrose content, since there is a weak negative correlation between these characters (Milligan et al., 1990). Selection for disease resistance might also reduce the impact of selecting for sucrose content. There is no evidence that disease resistance is negatively correlated with sucrose content, but disease susceptibility in a high sucrose genotype would eliminate that genotype from the breeding program.

A return to recurrent selection without inclusion of new material from the basic breeding program might be needed to specifically increase sucrose content. Kennedy (2005) reported that four cycles of recurrent single trait selection for juice Brix within a closed population produced genotypes with sucrose content >23% of juice. One clone had a sucrose content of 22.3% cane. This approach is currently being tried as a separate effort in Louisiana with the goal of providing very high sucrose genotypes that could be used as parents in the commercial breeding program. One genotype from the third round of this effort had a juice sucrose concentration of 21%, and a juice purity of 94% when harvested early in November 2007 (T.L. Tew, unpublished data). It remains to be seen whether inclusion of such genotypes with very high sucrose content as a parent in the commercial breeding program will further increase sucrose content in newly developed cultivars.

Another recent change in selection strategy has been an emphasis on juice quality very early in the harvest season. Recent cultivars such as HoCP 00-950 and L 97-128, both Generation 7 cultivars, have been noted to have more juice sucrose and higher purity earlier in the season than older cultivars (Gravois et al., 2008; Tew et al., 2009). It is possible that, had we harvested these experiments earlier in the harvest season, we might have seen significant differences in juice quality among the later Generations.

The significant change in Brix, sucrose, and purity with recurrent selection contrasts with the non-significant differences in fiber (Table 1). During the evaluation leading to eventual release, genotypes with more than 14% fiber or <11% fiber are eliminated. High fiber is undesirable because it reduces sugar extraction at the mill and increases wear on milling equipment. Genotypes with <11% fiber tend to lodge more, slowing harvest, and may not produce enough bagasse to fuel the milling process. This means that all cultivars are held to approximately the same standard when it comes to fiber, and this is borne out by the fiber data.

4.2. Estimating gains from selection

While the lack of statistical differences among the last four generations raises the possibility that a plateau has been reached in juice quality and yield, this experiment was not specifically designed to measure genetic gain. Edmé et al. (2005) used data from 33 years of production data from released cultivars and Stage IV selection trials to assess improvements in sucrose content, cane yield and sugar yield in the Florida sugarcane breeding program. They concluded that there was no evidence of yield plateaus for sucrose content and sugar yield in the Florida breeding program. Cox and Stringer (2006, 2007) used 25 years of production data from Queensland, Australia sugar mills to measure genetic gain of released cultivars in the breeding program there. They also concluded that gains in sucrose content were still being made. Using production data from the past may be misleading because of changes in production and harvesting practices that occur over time. For instance, during the 33-year period used by Edmé et al. (2005), 1968–2000, the Florida sugarcane industry started leaving the water table higher during the growing season in much of the sugarcane growing area (B. Glaz, 2010, personal communication), and shifted from harvesting by hand to harvesting by machine. Production changes over the 80 years represented by the cultivars in this study would be greater. There are, however, disadvantages to small plots, such as the cost of the space and labor involved in doing the study. Also, the environment can have a larger effect on small plots than on large ones. Milligan et al. (2007) showed that the residual variance for cane and sugar yield was larger in small plots than in large ones. A large residual variance can mask real genetic differences. However, Jackson and McRae (2001) demonstrated that competition among genotypes in one-row plots increased estimates of genetic variance for cane yield.

We did not measure insect damage or the effects of disease on the cultivars. Diseases are an important reason for cultivar turnover. Much of the selection effort in any breeding program is directed to responding to changes in diseases that occur over time. The major sugarcane diseases in Louisiana that influence selection decisions are brown rust (*Puccinia melanobethala*), sugarcane mosaic, sorghum mosaic, smut (*Ustilago scitaminea*), and leaf scald (*Xanthomonas albilineans*) (M.P. Grisham, 2009, personal communication).

5. Conclusion

This study provides evidence that sugarcane juice quality in late-harvested sugarcane has been increased by six cycles of recurrent selection for sucrose, but that a limit may have been reached for further improvement. The highest sucrose content observed was much lower than that achieved in more tropical environments. This is possibly due to the very short growing season, but could also have been caused by changes in selection strategy and the introgression of new *S. spontaneum* germplasm to improve disease resistance, cold tolerance, and crop longevity.

Acknowledgements

We would like to thank April Allen, Elta Duet, Jeannette Adams, Lawrence Lovell, Jr., Lionel Lomax, Halley Burleson, David Jones, Brenda King, and Jessica Brown for their assistance with this study. We would also like to thank Dr. Deborah Boykin for assistance with the statistical analyses.

Product and trademark names are given for information only and do not imply a recommendation or warranty over other suitable products.

References

Aitken, K.S., Jackson, P.A., McIntyre, C.L., 2006. Quantitative trait loci identified for sugar related traits in a sugarcane (*Saccharum* spp.) cultivar×*Saccharum officinarum* population. TAG Theoretical and Applied Genetics 112, 1306–1317.

Alwala, S., Kimbeng, C., Veremis, J., Gravois, K., 2009. Identification of molecular markers associated with sugar-related traits in a *Saccharum* interspecific cross. Euphytica 167 (1), 127–142.

Berding, N., 1997. Clonal improvement of sugarcane based on selection for moisture content: fact or fiction. Proceedings of the Australian Society of Sugar Cane Technologists 19, 245–253.

Breaux, R.D., 1984. Breeding to enhance sucrose content of sugarcane varieties in Louisiana. Field Crops Research 9, 59–67.

Cox, M.C., Stringer, J.K., 2006. Analysis of sugarcane productivity data: increases from new cultivars and improved management in Australia. In: Mercer, C.F. (Ed.), Proceedings of the 13th Australasian Plant Breeding Conference, 18–21 April 2006. Christchurch, NZ, pp. 1–5.

Cox, M.C., Stringer, J.K., 2007. Benchmarking genetic gains from new cultivars in Queensland using productivity data. Proceedings of the International Society of Sugar Cane Technologists 26, 624–631.

Deren, C.W., 1995. Genetic base of US mainland sugarcane. Crop Science 35 (4), 1195–1199.

Dunckelman, P.H., Breaux, R.D., 1972. Breeding sugarcane varieties for Louisiana with new germ plasm. Proceedings of the International Society of Sugar Cane Technologists 14, 233–239.

Edmé, S.J., Miller, J.D., Glaz, B., Tai, P.Y.P., Comstock, J.C., 2005. Genetic contribution to yield gains in the Florida sugarcane industry across 33 years. Crop Science 45 (1), 92–97.

Gravois, K.A., Bischoff, K.P., 2008. New sugarcane varieties to the rescue. Louisiana Agriculture 51 (2), 14–16.

Gravois, K.A., Bischoff, K.P., Milligan, S.B., Martin, F.A., Hoy, J.W., Reagan, T.E., Kimbeng, C.A., LaBorde, C.M., Hawkins, G.L., 2008. Registration of 'L 97-128' Sugarcane. Journal of Plant Regetrations 2 (1), 24–28.

Hogarth, D.M., 1987. Genetics of sugarcane. In: Heinz, D.J. (Ed.), Sugarcane Improvement through Breeding. Elsevier, Amsterdam, pp. 255–271.

Inman-Bamber, N.G., Muchow, R.C., Robertson, M.J., 2002. Dry matter partitioning of sugarcane in Australia and South Africa. Field Crops Research 76 (1), 71–84.

Jackson, P., McRae, T.A., 2001. Selection of sugarcane clones in small plots: effects of plot size and selection criteria. Crop Science 41 (2), 315–322.

Jannoo, N., Grivet, L., Seguin, M., Paulet, F., Domaingue, R., Rao, P.S., Dookun, A., D'Hont, A., Glaszmann, J.C., 1999. Molecular investigation of the genetic base of sugarcane cultivars. TAG Theoretical and Applied Genetics 99 (1–2), 171–184.

Johnson, R.M., Richard Jr., E.P., 2005. Sugarcane yield, sugarcane quality, and soil variability in Louisiana. Agronomy Journal 97 (3), 760–771.

Kennedy, A.J., 2005. Breeding improved cultivars for the Caribbean by utilisation of total biomass production. Proceedings of the International Society of Sugar Cane Technologists 25, 491–499.

Legendre, B.L., 1992. The core/press method for predicting the sugar yield from cane for use in cane payment. Sugar Journal 54 (9), 2–7.

Legendre, B.L., Henderson, M.T., 1972. The history and development of sugar yield calculations. Proceedings of the American Society of Sugar Cane Technologists 2 (ns), 10–18.

Lingle, S.E., Viator, R.P., Johnson, R.M., Tew, T.L., Boykin, D.L., 2009. Recurrent selection for sucrose content has altered growth and sugar accumulation in sugarcane. Field Crops Research 113 (3), 306–311.

Littell, R.C., Milliken, G.A., Stroup, W.W., Wolfinger, R.D., 1996. SAS System for Mixed Models. SAS Institute Inc., Cary, NC.

Milligan, S.B., Balzarini, M., Gravois, K.A., Bischoff, K.P., 2007. Early stage sugarcane selection using different plot sizes. Crop Science 47 (5), 1859–1864.

Milligan, S.B., Gravois, K.A., Bischoff, K.P., Martin, F.P., 1990. Crop effects on genetic relationships among sugarcane traits. Crop Science 30, 927–931.

Ming, R., Liu, S.C., Bowers, J.E., Moore, P.H., Irvine, J.E., Paterson, A.H., 2002a. Construction of a *Saccharum* consensus genetic map from two interspecific crosses. Crop Science 42 (2), 570–583.

Ming, R., Liu, S.C., Moore, P.H., Irvine, J.E., Paterson, A.H., 2001. QTL analysis in a complex autopolyploid, genetic control of sugar content in sugarcane. Genome Research 11, 2075–2084.

Ming, R., Wang, Y.W., Draye, X., Moore, P.H., Irvine, J.E., Paterson, A.H., 2002b. Molecular dissection of complex traits in autopolyploids: mapping QTLs affecting sugar yield and related traits in sugarcane. Theoretical and Applied Genetics 105 (2–3), 332–345.

Muchow, R.C., Robertson, M.J., Wood, A.W., 1996. Growth of sugarcane under high input conditions in tropical Australia. II. Sucrose accumulation and commercial yield. Field Crops Research 48 (1), 27–36.

Reffay, N., Jackson, P.A., Aitken, K.S., Hoarau, J.-Y., D'Hont, A., Besse, P., McIntyre, C.L., 2005. Characterisation of genome regions incorporated from an important wild relative into Australian sugarcane. Molecular Breeding 15 (4), 367–381.

Singh, G., Chapman, S.C., Jackson, P.A., Lawn, R.J., 2002. Lodging reduces sucrose accumulation of sugarcane in the wet and dry tropics. Australian Journal of Agricultural Research 53 (11), 1183–1195.

Tew, T.L., Dufrene, E.O., Garrison, D.D., White, W.H., Grisham, M.P., Pan, Y.B., Richard Jr., E.P., Legendre, B.L., Miller, J.D., 2009. Registration of 'HoCP 00-950' Sugarcane. Journal of Plant Regetrations 3 (1), 42–50.